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Sub-MeV electron precipitation driven by EMIC waves in plasmaspheric plumes at high L-shells

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2 **Sub-MeV Electron Precipitation Driven by EMIC waves in Plasmaspheric**
3 **Plumes at High L shells**

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21 **Key Points:**

- 22
- 23 • EMIC-driven sub-MeV electron precipitation is observed by ELFIN, supported by
conjugate THEMIS wave observations in the afternoon sector.
 - 24 • Sub-MeV electron precipitation occurs at $8 < L < 10.5$ in plasmaspheric plume regions,
25 where trapped MeV electrons are nearly absent.
 - 26 • Quasi-linear modeling suggests that a high f_{pe}/f_{ce} ratio in plume at high L shells is critical
27 for driving sub-MeV electron precipitation.
28

29 **Abstract**

30 Electromagnetic ion cyclotron (EMIC) waves are known to be efficient for precipitating > 1 MeV
31 electrons from the magnetosphere into the upper atmosphere. Despite considerable evidence
32 showing that EMIC-driven electron precipitation can extend down to sub-MeV energies, the
33 precise physical mechanism driving sub-MeV electron precipitation remains an active area of
34 investigation. In this study, we present an electron precipitation event observed by ELFIN
35 CubeSats on 11 January 2022, exclusively at sub-MeV energy at $L \sim 8-10.5$, where trapped MeV
36 electrons were nearly absent. The THEMIS satellites observed conjugate H-band and He-band
37 EMIC waves and hiss waves in plasmaspheric plumes near the magnetic equator. Quasi-linear
38 diffusion results demonstrate that the observed He-band EMIC waves, with a high ratio of plasma
39 to electron cyclotron frequency, can drive electron precipitation down to ~ 400 keV. Our findings
40 suggest that exclusive sub-MeV precipitation (without concurrent MeV precipitation) can be
41 associated with EMIC waves, especially in the plume region at high L shells.

42 **Plain Language Summary**

43 Energetic electrons precipitating from the Earth's magnetosphere have a significant influence on
44 the ionosphere and upper atmosphere, including modulating ionospheric conductance and
45 producing aurorae. As one of the major drivers of energetic electron precipitation, EMIC waves
46 are reported to be efficient in precipitating > 1 MeV electrons. Recently, multiple studies, including
47 both observation and modeling, showed that electron precipitation driven by EMIC waves can also
48 extend down to sub-MeV energies. However, the precise physical mechanism by which EMIC
49 waves drive sub-MeV electron precipitation is still under investigation. In this study, we present a
50 sub-MeV electron precipitation event driven by EMIC waves in plasmaspheric plumes at high L
51 shells ($L \sim 8-10.5$), where trapped electrons at > 1 MeV are nearly absent. The Electron Loss and
52 Fields INvestigation (ELFIN) CubeSats, which provide high energy and pitch angle resolution
53 electron measurements, are utilized to identify EMIC-driven precipitation signatures. Conjugate
54 wave and plasma measurements are obtained from the Time History of Events and Macroscale
55 Interactions during Substorms (THEMIS) satellite near the magnetic equator. Our results
56 demonstrate that EMIC waves in plasmaspheric plumes at high L shells could play an important
57 role in driving sub-MeV electron precipitation.

58 **1 Introduction**

59 Electromagnetic ion cyclotron (EMIC) waves (0.1–10 Hz) are electromagnetic waves that
60 typically occur in multiple distinct bands: H⁺ band, He⁺ band, O⁺ band, H⁺⁺ band, O⁺⁺ band, and
61 N⁺ band (e.g., Anderson and Fuselier, 1993; Bashir and Ilie, 2021; Bogdanov et al., 2003;
62 Engebretson et al., 2018; Kozyra et al., 1984; Lee et al., 2019; Usanova et al., 2024; Yu et al.,
63 2021), with frequencies below the corresponding ion gyrofrequencies. They are typically
64 generated by temperature anisotropy of injected ring current ions during enhanced geomagnetic
65 activities (Fraser et al., 2010), compression of the dayside magnetosphere (Anderson and Hamilton
66 1993; Liu et al., 2019; Usanova et al., 2012) or through the change in the flux and pitch-angle
67 anisotropy of the resonant ion population caused by large-amplitude ULF oscillations (Thorne et
68 al., 2006 and references therein).

69 EMIC waves are known to be efficient for precipitating \sim MeV electrons and producing the fast
70 loss of radiation belt electrons (e.g., Bruno et al., 2022; Lyu et al., 2022; Mourenas et al., 2016;
71 Qin et al., 2018, 2019, 2020, 2024; Shumko et al., 2022; Xiang et al., 2017; Zhang et al., 2016).

72 Meredith et al. (2003) statistically investigated the minimum resonance energy (E_{\min}) for quasi-
 73 linear interactions between EMIC waves and electrons using Combined Release and Radiation
 74 Effects Satellite (CRRES) data and suggested that only a small fraction ($\sim 11.3\%$) of the observed
 75 EMIC waves can drive electron precipitation below 2 MeV. By considering the finite width of the
 76 EMIC wave frequency spectrum, Ukhorskiy et al. (2010) showed that E_{\min} can be as low as 400
 77 keV, when there is sufficient wave power close to the ion gyrofrequencies. However, the
 78 appreciable wave power crossing f_{cHe^+} reported by Ukhorskiy et al. (2010) requires sufficient hot
 79 He^+ populations. This leads to a finite wave number at $\sim f_{\text{cHe}^+}$ frequency and consequently results
 80 in an E_{\min} of a few MeV (Chen et al., 2011). Chen et al. (2019) conducted a 5.5-year analysis of
 81 data from the Van Allen Probes measurements and showed that only less than 1% of H-band EMIC
 82 waves can resonate with sub-MeV electrons, and none of the He-band EMIC waves can do so.

83
 84 Recent studies have provided strong observational evidence that EMIC waves can precipitate
 85 electrons with energies well below 1 MeV (Capannolo et al., 2019, 2021; Hendry et al., 2017). In
 86 particular, Hendry et al., (2017) suggested that EMIC-driven electron precipitation has a peak flux
 87 predominantly at ~ 240 keV. Such low E_{\min} can be achieved through non-resonant interactions
 88 (Chen et al., 2016; An et al., 2022, 2024), nonlinear fractional resonance with oblique waves
 89 (Hanzelka et al., 2023, 2024), or a sufficiently high ratio of plasma frequency to electron
 90 gyrofrequency ($f_{\text{pe}}/f_{\text{ce}}$) through cyclotron resonant interactions (Li et al., 2007; Summers et al.,
 91 2003). Usanova et al. (2013) and Grison et al. (2021) found that EMIC wave occurrence rate in
 92 duskside plumes (12-16 MLT) increases toward the magnetopause, reaching up to
 93 $\sim 20\%$. Additionally, Darrouzet et al. (2008) found that plasmaspheric plumes have a high
 94 probability of being detected in the afternoon sector (15–16 MLT) at $6 < L < 9$. Such plumes at
 95 high L shells could be characterized by high values of $f_{\text{pe}}/f_{\text{ce}}$ due to their high electron density and
 96 low magnetic field strength, potentially lowering E_{\min} , which enables EMIC waves to scatter sub-
 97 MeV electrons. Recent statistical studies have shown that while EMIC-driven precipitation events
 98 are most commonly observed from dusk to pre-midnight at $L \sim 5-7$, a second class of events
 99 occurs at higher L -shells at $\sim 7-12$ (Angelopoulos et al., 2023; Capannolo et al., 2023), with E_{\min}
 100 decreasing as L increases (Angelopoulos et al., 2023; Grach et al., 2024). Additionally, at such
 101 high L -shells, the trapped flux at $> \text{MeV}$ energies is likely too low to be detected, suggesting that
 102 EMIC waves may predominantly drive only sub-MeV electron precipitation at high L shells in
 103 plumes. However, despite these insights, the precise role of EMIC waves in driving sub-MeV
 104 electron precipitation at higher L -shells in plumes remains elusive.

105
 106 In this study, we present a fortuitous case of simultaneous observations of EMIC waves and
 107 electron precipitation occurring down to ~ 100 s of keV for five consecutive orbits in plumes at high
 108 L -shells. By leveraging the high-energy and pitch-angle resolution measurements from the
 109 Electron Loss and Fields INvestigation (ELFIN) mission (Angelopoulos et al., 2020) for multiple
 110 orbits at Low Earth Orbit (LEO), we identify clear EMIC-driven signatures of the observed sub-
 111 MeV electron precipitation. We conduct quasi-linear diffusion modeling to determine if EMIC
 112 waves observed by Time History of Events and Macroscale Interactions during Substorms
 113 (THEMIS) (Angelopoulos, 2008) satellites can drive the observed electron precipitation to sub-
 114 MeV energies. Finally, we quantitatively compare the modeled precipitation ratio with the
 115 observations.

116 2 Observations

117 2.1 Data

118 In this study, electron measurements from the ELFIN CubeSats are utilized to analyze the electron
119 precipitation at LEO. The ELFIN mission, which consists of dual probes, was launched at an
120 altitude of ~ 450 km on September 15, 2018, with an orbital period of ~ 1.5 hours. The electron
121 head onboard the Energetic Particle Detector (EPD) measures electrons from ~ 50 keV to 6 MeV,
122 with an energy resolution of $\Delta E/E < 40\%$. The spin axis of each CubeSat is maintained
123 perpendicular to the orbital plane, providing full pitch-angle resolution of electrons twice per spin
124 (~ 3 s). The measurements in each spin are subdivided into 16 bins, yielding a pitch-angle
125 resolution of $\sim 22.5^\circ$. Such pitch-angle and energy-resolved measurements are critical for
126 identifying the driver of energetic electron precipitation.

127 We also utilize conjugated measurements of waves and plasmas from THEMIS satellites located
128 near the magnetic equator. Specifically, the Fluxgate Magnetometer (FGM) instrument (Auster et
129 al., 2008) is used to measure low-frequency magnetic field fluctuations (up to 64 Hz). To compute
130 the spectral density of EMIC waves, a fast Fourier transform method is applied, using a window
131 size of 256 s and employing a shifted time window of 32 s. Additionally, the magnetic spectral
132 density observed by the Search Coil Magnetometer (SCM) (Roux et al., 2008) is adopted to
133 analyze whistler mode wave properties. The total electron density is inferred from the spacecraft
134 potential (Pedersen et al., 2008) measured by the Electric Field Instrument (EFI) (Bonnell et al.,
135 2008). The potential derived density is also compared with density measured by electrostatic
136 analyzer (ESA) (McFadden et al., 2009).

137 2.2 Electron precipitation observed by ELFIN

138 Figure 1 shows an overview of sub-MeV electron precipitation observed by ELFIN. The top and
139 middle panels in Figures 1a–e show locally trapped and precipitating electron energy fluxes,
140 respectively. The precipitation ratios, determined by the ratios of precipitating energy flux to the
141 locally trapped energy flux, are shown in the bottom panels of Figures 1a–e. When calculating the
142 precipitation ratio, we removed the data with low trapped electron counts (counts $< 4/s$) which lead
143 to unphysically high ratios. Both ELFIN-A and B observed electron precipitation from all five
144 consecutive duskside orbits during the 3-hr time interval of 04:09–07:19 UT on 11 January 2022.
145 Specifically, the intervals with electron precipitation likely driven by EMIC waves are marked by
146 the bars with different colors in Figures 1a–1e. During these intervals, the precipitation ratio is
147 above ~ 0.2 for energies ranging from ~ 200 keV to < 1 MeV and increases as energy increases.
148 The latter feature suggests that the prevailing wave and plasma conditions are conducive to EMIC
149 waves to drive the observed sub-MeV electron precipitation. This is consistent with the fact that
150 EMIC-driven precipitation becomes progressively more efficient with increasing energy and is
151 most effective at \sim MeV energies (Angelopoulos et al., 2023; Capannolo et al., 2023). Modest
152 precipitation was also observed for electrons below 200 keV at lower L shells ($L < \sim 8$), with a
153 precipitation ratio below ~ 0.3 , and the precipitation ratio decreases as energy increases, likely
154 driven by whistler-mode waves (e.g., Shen et al., 2023). In this work, we mainly focus on electron
155 precipitation associated with EMIC-driven signatures. The energy range of the EMIC-driven
156 electron precipitation varies from orbit to orbit. For precipitation ratios > 0.1 , the lowest cutoff
157 energies of electron precipitation range from 60 keV to 300 keV, and the highest cutoff energies

158 range from ~ 600 keV to ~ 1 MeV. This feature, characterized by electron precipitation exclusively
 159 below 1 MeV, is reasonable as the trapped relativistic electron flux level >1 MeV was too low,
 160 thus little electron precipitation above 1 MeV was observed. The locations of ELFIN during
 161 observed EMIC-driven signatures are shown in Figure 1f. It is evident that electron precipitation
 162 occurs at very high L shells, ranging from 8 to 10.5 on the duskside (MLT ~ 16.4 – 17). Interestingly,
 163 the outer boundary of the precipitation moves inward over time, from $L \sim 10.5$ at 04:12:00 UT to
 164 $L \sim 8.5$ at 07:18:40 UT, suggesting the corresponding evolution of the wave-particle interaction
 165 region. It is worthwhile to note that the corresponding L-shell of the ELFIN satellites was
 166 calculated using the TS05 model (Tsyganenko & Sitnov, 2005). Fortunately, THEMIS-A, D and
 167 E were in a conjugate location with ELFIN-A in both time and space during the first orbit (Figure
 168 1f), enabling a direct comparison between the observations of waves and electron precipitation.
 169 The THEMIS observations can also test the hypothesis that EMIC waves alone can drive the
 170 observed electron precipitation.

171 **2.3 Conjugated plasma waves observed by THEMIS**

172 The waves and plasma parameters measured by THEMIS-A, D and E near the equator are shown
 173 in Figure 2. Figures 2a and 2b show the locations of THEMIS-A (black) and ELFIN-A (blue).
 174 ELFIN-A was located at $L \sim 10.7$ and MLT ~ 16.4 at the time of the precipitation observation
 175 (04:12 UT). THEMIS-A was located at MLT ~ 15 – 15.5 and $L \sim 9$ – 10 when EMIC waves were
 176 observed. THEMIS-A (03:30–04:30 UT), D (02:00–03:40 UT) and E (04:10–05:00 UT) all
 177 recorded intense quasi-parallel propagating EMIC waves (Figures 2c, 2d, 2j, 2k, 2q and 2r), with
 178 intense wave power in the He-band and modest wave power in the H-band. THEMIS-A, D and E
 179 also observed whistler-mode chorus between $0.1 f_{ce}$ and $0.5 f_{ce}$ and broadband hiss waves (Figure
 180 2e, 2l and 2s), with chorus waves located at lower L-shells than those of the EMIC waves. These
 181 locations are consistent with the ELFIN observations of chorus-driven electron precipitation at L
 182 $< \sim 8$ and EMIC-driven precipitation at $L > \sim 8$. Additionally, whistler-mode hiss waves occurred
 183 simultaneously with EMIC waves. The black lines in Figures 2f, 2m and 2t show the total electron
 184 density inferred from the spacecraft potential. It is evident that both EMIC waves and hiss waves
 185 intensified within the high-density plume region, where the density shows a localized increase at
 186 $L \sim 8$ – 10 . The plume region was observed shortly after the transient magnetopause crossings ($L \sim$
 187 11) on the duskside, which might be associated with the enhanced convection electric field during
 188 periods of elevated geomagnetic activity (e.g., Darrouzet et al., 2008; Goldstein et al., 2004, 2014).
 189 The highest density was detected by THEMIS-A, corresponding to an exceptionally high value of
 190 f_{pe}/f_{ce} of about 30 (Figure 2g). The density measured by ESA (from a few eV to ~ 30 keV, not
 191 shown) exhibits a similar trend to the density inferred from spacecraft potential. However, the
 192 overall electron density calculated from the ESA measurement is lower, likely because electrons
 193 with energies below a few eV are not detectable by the ESA instrument. We adopt the most intense
 194 wave power for EMIC and hiss waves (marked by two dashed vertical magenta lines) for a further
 195 analysis.

196 **3 Comparison of modeled electron precipitation and observations**

197 To evaluate whether the sub-MeV electron precipitation can be driven by the observed waves, the
 198 pitch angle scattering rates driven by He-band EMIC waves (over 03:35–04:00 UT), H-band EMIC
 199 waves (over 03:35–03:50 UT) and whistler-mode hiss waves (03:35–04:00 UT) observed by
 200 THEMIS-A were computed using the Full Diffusion Code (Ma et al., 2019, 2020, 2021; Ni et al.,

201 2008, 2015; Qin et al., 2021, 2024). Figures 3a–3c show the corresponding bounce-averaged pitch
 202 angle diffusion coefficients ($\langle D_{\alpha\alpha} \rangle$), which were calculated based on the averaged wave
 203 spectral distributions and plasma parameters measured by THEMIS-A during the above intervals.
 204 The lower (upper) cutoff frequencies are 0.27 (0.48) f_{cH}^+ for H-band EMIC waves and 0.53 (0.98)
 205 f_{cHe}^+ for He-band EMIC waves, obtained by requiring the wave intensity to be above the instrument
 206 noise level. The total electron density is derived from the spacecraft potential (Figure 2f) measured
 207 by THEMIS-A and assumed to be constant along the field lines. The corresponding value of f_{pe}/f_{ce}
 208 is ~ 32 . It is worth noting that such a high value of f_{pe}/f_{ce} , which can efficiently reduce the minimum
 209 resonant energy, has been rarely reported. For EMIC waves, the cyclotron harmonic resonance
 210 numbers considered in the calculation are from -5 to 5, including the Landau resonance. The waves
 211 are assumed to be quasi field-aligned at the equator, consistent with the observed wave normal
 212 angle values shown in Figure 2d, 2k and 2r, and become oblique at higher latitudes, similarly to
 213 the latitudinally-varying model by Ni et al. (2015). Cold ion compositions are assumed to be 70%
 214 for H^+ , 20% for He^+ , and 10% for O^+ . The averaged wave amplitudes for H-band and He-band
 215 EMIC waves are 75 pT (over 03:35–03:50 UT) and 410 pT (over 03:35–04:00 UT), respectively.
 216 In this event, H-band EMIC waves have no contribution to electron precipitation below 10 MeV
 217 (not shown). However, He-band EMIC waves can efficiently precipitate >400 keV electrons, with
 218 bounce-averaged pitch angle diffusion coefficients ($\langle D_{\alpha\alpha} \rangle$) ranging from 10^{-4} to $10^{-2} s^{-1}$ near
 219 the loss cone (Figure 3a). This is comparable to the minimum energy of the electron precipitation
 220 observed by ELFIN (~ 60 – 300 keV) and indicates that He-band could potentially be responsible
 221 for the observed electron precipitation down to ~ 400 keV. The potential effects of non-linear
 222 fractional resonance (Hanzelka et al., 2023, 2024) and non-resonant scattering (An et al., 2022,
 223 2024; Chen et al., 2016) can cause electron precipitation below the minimum resonance energy
 224 and may also account for the weak precipitation below 400 keV observed by ELFIN; however,
 225 this comparison will be a subject of future investigation. For hiss waves, 10 orders of resonant
 226 harmonics and Landau resonance are included to calculate the diffusion coefficients. The bounce-
 227 averaged diffusion coefficients show that hiss waves can scatter energetic electrons mainly below
 228 ~ 20 keV near the loss cone. However, they can interact with $> \sim 100$ keV electrons with equatorial
 229 pitch angle $> 45^\circ$ and thus move the electrons towards the smaller pitch angles, where EMIC waves
 230 can take over to further precipitate the electrons into the loss cone.

231
 232 Using the pitch angle diffusion coefficients at the loss cone, denoted as $\langle D_{\alpha\alpha} \rangle|_{LC}$, we further
 233 quantify the electron precipitation ratio driven by He-band EMIC waves and hiss waves with the
 234 loss cone filling index, denoted as $\chi(E)$ (Ma et al., 2020; Ni et al., 2014; Shen et al., 2023). This
 235 index is defined as the ratio of electron flux just outside the loss cone to the electron flux near the
 236 center of the loss cone under the diffusion equilibrium state (Kennel and Petschek, 1966) and can
 237 be estimated as follows:

$$238 \quad \chi(E) = \frac{2 \int_0^1 I_0[Z_0(E)\tau] \cdot \tau \cdot d\tau}{I_0[Z_0(E)]} \quad (1)$$

239 Here I_0 is the modified Bessel function of the first kind and $Z_0 = \sqrt{\frac{D_{SD}}{\langle D_{\alpha\alpha} \rangle|_{LC}}}$, where D_{SD} is the
 240 strong diffusion limit, and τ is an integration variable.

241
 242 The calculated loss cone filling index is shown as the solid black line in Figure 3d, which is overall
 243 consistent with the observed precipitation ratios from ELFIN. The colored lines with error bars

244 show the uncertainty of the measurements, determined from the standard deviation of the
 245 precipitation ratio during each interval at each energy channel. Both the observed and modeled
 246 precipitation ratios are close to 1 at energies above 500 keV and tend to decrease as energy
 247 decreases. It is also worth noting that even though the modeled electron precipitation ratio is ~ 1.0
 248 for electrons above 1 MeV, no precipitation was observed at the MeV energy except during
 249 05:45:00–05:45:39 UT (green line). This is due to the fact that there were few trapped electrons
 250 available to be precipitated at such high energy and high L shells. The quantitative analysis
 251 demonstrates that the observed electron precipitation above 400 keV can be well explained by He-
 252 band EMIC waves through quasilinear theory. The modeled E_{\min} is ~ 400 keV, while the observed
 253 lowest cutoff energy where precipitation ratios are > 0.1 ranges from 60 to 300 keV. The upper
 254 bound of the observed range (300 keV) is within 25% of the modeled value, which is reasonable
 255 given the energy resolution of the instrument. However, the model does not account for
 256 precipitation in the lower energy range (60–300 keV), which warrants further investigation. We
 257 also evaluate E_{\min}^* , which is the energy corresponding to half the peak in the measured
 258 precipitation ratio below its peak, as a proxy for the theoretical minimum resonance energy
 259 corresponding to significant wave-driven scattering toward the loss cone (Angelopoulos et al.,
 260 2023). As shown in Figure 3, most values of E_{\min}^* (colored diamonds) range from ~ 300 keV to
 261 ~ 450 keV, which is close to the modeled result. The observed E_{\min}^* from 05:39:06 UT to 05:39:13
 262 UT is lower (~ 150 keV), potentially attributed to the spatial and temporal evolution of EMIC wave
 263 properties.

264
 265 Considering the uncertainty in electron density derived from the spacecraft potential, we calculated
 266 the diffusion coefficients based on half and double values of the measured density (Figures 4a and
 267 4b). E_{\min} decreases to ~ 100 keV with double values of the measured density and increases to ~ 700
 268 keV with half values of the measured density. The corresponding loss cone filling index is shown
 269 as the dashed and dotted black lines in Figure 4c. The modeled loss cone filling index with double
 270 (half) density also agrees well with the upper (lower) boundary of the observed precipitation ratio.
 271

272 As EMIC wave-driven electron precipitation may also be sensitive to cold ion compositions (Qin
 273 et al., 2019; Ross et al., 2022), we model electron precipitation under varying cold plasma
 274 compositions. Figure 5 shows the pitch angle diffusion coefficients and precipitation ratios for
 275 varying cold ion compositions, with the same density as used in Figure 3. Comparing Figure 3c to
 276 Figure 5a, it is shown that E_{\min} changes only slightly as the O^+ composition increases by 10%
 277 (from $H^+ : He^+ : O^+ = 0.7:0.2:0.1$ to $0.6:0.2:0.2$). However, when the percentage of He^+ increases
 278 (Figure 5b, $H^+ : He^+ : O^+ = 0.6:0.39:0.01$), E_{\min} decreases to approximately 200 keV near the loss
 279 cone, aligning more closely with observations. Conversely, when the cold ion composition is
 280 dominated by H^+ (Figure 5c, $H^+ : He^+ : O^+ = 0.99:0.005:0.005$), E_{\min} increases significantly to ~ 2
 281 MeV.

282 4 Summary

283 In this study, we report a direct observation of sub-MeV electron precipitation by the ELFIN
 284 CubeSats, characterized by an increasing precipitation ratio as a function of energy (a clear EMIC
 285 wave-driven signature) and EMIC waves observed in the conjugate equatorial region by THEMIS.
 286 In particular, EMIC waves occurred in the duskside plume at very high L shells ($L \sim 8$ – 10.5). The
 287 associated electron precipitation occurred primarily below 1 MeV and lasted at least for three hours.

288 The lowest cutoff energies of the electron precipitation range from 60 keV to 300 keV and the
289 highest cutoff energies range from ~600 keV to ~1 MeV.

290 Using quasi-linear theory with cold plasma assumptions, we demonstrate that the He-band EMIC
291 waves played a major role in driving the electron precipitation at energies above ~ 400 keV. The
292 modeled minimum electron energy for cyclotron resonance with helium-band EMIC waves in this
293 specific case is lower than previous modeled results obtained from quasi-linear resonance studies
294 in the radiation belt at $L < 6$ (e.g., Bruno et al., 2022; Hogan et al., 2021, 2023; Qin et al., 2019;
295 Zhang et al., 2021). For instance, Zhang et al. (2021) showed that most He-band EMIC wave-
296 driven electron precipitation events have an E_{\min} of 1.0–2.4 MeV. Capannolo et al. (2023)
297 demonstrated that quasilinear modeling could drive EMIC-driven electron scattering down to 250
298 keV. However, the simulation was based on statistical observations of EMIC waves at L
299 ~6.5, focusing exclusively on cases with wave amplitudes greater than 1 nT. Capannolo et al.
300 (2023) also suggested that the statistical properties of EMIC waves in the simulation may differ
301 from those driving the precipitation observed by ELFEN, emphasizing the need for one-to-one
302 conjunction analyses to evaluate the quasi-linear effect of EMIC-driven precipitation. The E_{\min} of
303 approximately 400 keV in this case is attributed to its occurrence in the plume region at higher L -
304 shells, where the magnetic field is weaker while the density is higher. These conditions result in
305 high ratios of plasma to electron cyclotron frequency, which subsequently lowers E_{\min} . Given the
306 fact that the occurrence of EMIC waves peaks over $L \sim 8$ –10 (Grison et al., 2021; Kim et al., 2016;
307 Usanova et al., 2013) and the high chance of detecting duskside plumes at such high L -shells
308 (Darrouzet et al., 2008), our findings imply that resonant interactions with EMIC waves could
309 potentially play an important role in sub-MeV electron precipitation, particularly when the plume
310 region extends to very high L -shells.

311 The modeled E_{\min} is approximately 400 keV, while the observed lowest cutoff energy ranges
312 between 60 and 300 keV. The upper limit of this range (300 keV) is within 25% of the modeled
313 value, which is a reasonable agreement considering the energy resolution of the EPD instrument.
314 However, the model does not account for precipitation in the lower energy range (60-300 keV).
315 This might be due to the uncertainty in the density measurement or the assumption in the cold ion
316 composition. To address this problem, we evaluate the sensitivity of E_{\min} to background electron
317 density (Figure 4) and cold ion compositions (Figure 5) for this specific event at high L -shells in
318 the plume. When the measured density is doubled, E_{\min} decreases to ~100 keV, whereas halving
319 the density increases E_{\min} to ~700 keV (Figure 4). In terms of ion composition, a higher percentage
320 of He^+ can efficiently decrease E_{\min} to 200 keV near the loss cone, aligning more closely with
321 observations (Figure 5b). In contrast, when the composition is dominated by H^+ , E_{\min} increases
322 significantly (Figure 5c). The weak electron precipitation (with a precipitation ratio < 0.3) below
323 400 keV could also be attributed to non-resonant or non-linear effects (An et al., 2022; Chen et al.,
324 2016; Hanzelka et al., 2023, 2024), which can cause electron precipitation below the minimum
325 resonance energy. In this case, the averaged wave amplitude is around ~410 pT, less than 1% of
326 the background magnetic field (~50-70 nT) and is thus unlikely to drive strong non-resonant or
327 fractionally resonant scattering. However, the peak wave power might be sufficient to cause
328 notable non-resonant or fractionally resonant scattering. However, evaluating these effects is
329 beyond the scope of this study and will be investigated in future research. We also evaluate E_{\min}^* ,
330 defined as the energy at which the measured precipitation ratio reaches half its peak value below
331 the maximum. This serves as a proxy for the theoretical minimum resonance energy corresponding
332 to significant wave-driven scattering toward the loss-cone. Most E_{\min}^* values range from ~300

333 keV to ~ 450 keV, aligning more closely with the modeled results compared to the definition of
334 cutoff energy using precipitation ratios greater than 0.1.

335 In summary, our findings highlight that EMIC waves can drive electron precipitation exclusively
336 within the sub-MeV range (without MeV precipitation), particularly in the plume regions at high
337 L shells, where trapped \sim MeV electrons are mostly absent. Future research should focus on
338 examining the EMIC wave properties in such regions to better understand their role in sub-MeV
339 electron dynamics and their broader impact on magnetosphere-ionosphere coupling.

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348

349 **Open Research**

350 Data from THEMIS mission is used for plasma and wave measurements near the equator
351 (THEMIS team, 2008). ELFIN EPDE data are used for electron energy flux measurement
352 (Angelopoulos et al., 2018). Data used for the figures in the manuscript are available from (Qin
353 et al., 2025)
354
355

356 **References**

- 357 An, X., Artemyev, A., Angelopoulos, V., Zhang, X., Mourenas, D., & Bortnik, J. (2022).
358 Nonresonant scattering of relativistic electrons by electromagnetic ion cyclotron waves in Earth's
359 radiation belts. *Physical Review Letters*, 129(13), 135101.
360 <https://doi.org/10.1103/PhysRevLett.129.135101>
- 361 An, X., Artemyev, A., Angelopoulos, V., Zhang, X.-J., Mourenas, D., Bortnik, J., and Shi X.
362 (2024). Nonresonant scattering of energetic electrons by electromagnetic ion cyclotron waves:
363 Spacecraft observations and theoretical framework. *Journal of Geophysical Research: Space*
364 *Physics*, 129, e2023JA031863. <https://doi.org/10.1029/2023JA031863>
- 365 Anderson, B. J., & Fuselier, S. A. (1993). Magnetic pulsations from 0.1 to 4.0 Hz and associated
366 plasma properties in the Earth's subsolar magnetosheath and plasma depletion layer. *Journal of*
367 *Geophysical Research*, 98(A2), 1461–1479. <https://doi-org.ezproxy.bu.edu/10.1029/92JA02197>
- 368 Anderson, B. J., and D. J. Hamilton (1993), Electromagnetic ion cyclotron waves stimulated by
369 modest magnetospheric compressions, *J. Geophys. Res.*, 98, 11,369–11,382,
370 doi:10.1029/93JA00605.
- 371 Angelopoulos, V. (2008), The THEMIS mission, *Space Sci. Rev.*, 141, 5–34, doi:10.1007/s11214-
372 008-9336-1.
- 373 Angelopoulos, V. et al. (2018), ELFIN/EPDE, [Dataset] [https://themis-](https://themis-data.igpp.ucla.edu/elfindata/)
374 [data.igpp.ucla.edu/elfindata/](https://themis-data.igpp.ucla.edu/elfindata/).
- 375 Angelopoulos, V., Tsai, E., Bingley, L. et al. The ELFIN Mission. *Space Sci Rev* 216, 103 (2020).
376 <https://doi.org/10.1007/s11214-020-00721-7>.
- 377 Angelopoulos, V., Zhang, XJ., Artemyev, A.V. et al. Energetic Electron Precipitation Driven by
378 Electromagnetic Ion Cyclotron Waves from ELFIN's Low Altitude Perspective. *Space Sci*
379 *Rev* 219, 37 (2023). <https://doi.org/10.1007/s11214-023-00984-w>.
- 380 Auster, H. U., et al. (2008), The THEMIS fluxgate magnetometer, *Space Sci. Rev.*, 141, 235–264,
381 doi:10.1007/s11214-008-9365-9.
- 382 Bashir, M. F., & Ilie, R. (2021). The first observation of N⁺ electromagnetic ion cyclotron
383 waves. *Journal of Geophysical Research: Space Physics*, 126,
384 e2020JA028716. doi:10.1029/2020JA028716
- 385 Bogdanov, A. T., Glassmeier, K.-H., Musmann, G., Dougherty, M. K., Kellock, S., Slootweg, P.,
386 & Tsurutani, B. (2003). Ion cyclotron waves in the Earth's magnetotail during CASSINI's Earth
387 swing-by. *Annals of Geophysics*, 21(10), 2043–2057. doi:10.5194/angeo-21-2043-2003
- 388 Bonnell, J. W., F. S. Mozer, G. T. Delory, A. J. Hull, R. E. Ergun, C. M. Cully, V. Angelopoulos,
389 and P. R. Harvey (2008). The Electric Field Instrument (EFI) for THEMIS, *Space Sci. Rev.*, 141,
390 303–341, doi:10.1007/s11214-008-9469-2.
- 391 Bruno, A., Blum, L. W., de Nolfo, G. A., Kataoka, R., Torii, S., Greeley, A. D., et al.
392 (2022). EMIC-wave driven electron precipitation observed by CALET on the International Space
393 Station. *Geophysical Research Letters*, 49,
394 e2021GL097529. <https://doi.org/10.1029/2021GL097529>

- 395 Capannolo, L., Li, W., Spence, H., Johnson, A. T., Shumko, M., Sample, J., & Klumpar, D. (2021).
396 Energetic electron precipitation observed by FIREBIRD-II potentially driven by EMIC waves:
397 Location, extent, and energy range from a multievent analysis. *Geophysical Research Letters*, 48,
398 e2020GL091564. <https://doi.org/10.1029/2020GL091564>
- 399 Capannolo, L., Li, W., Ma, Q., Qin, M., Shen, X.-C., Angelopoulos, V., Artemyev, A., Zhang, X.-
400 J., Hanzelka, M. (2023). Electron Precipitation Observed by ELFIN Using Proton Precipitation as
401 a Proxy for Electromagnetic Ion Cyclotron (EMIC) Waves. *Geophysical Research Letters*,
402 <https://doi.org/10.1029/2023GL103519>
- 403 Chen, L., R. M. Thorne, and J. Bortnik (2011), The controlling effect of ion temperature on EMIC
404 wave excitation and scattering, *Geophys. Res. Lett.*, 38, L16109, doi:10.1029/2011GL048653.
- 405 Chen, L., Thorne, R. M., Bortnik, J., and Zhang, X.-J. (2016), Nonresonant interactions of
406 electromagnetic ion cyclotron waves with relativistic electrons, *J. Geophys. Res. Space Physics*,
407 121, 9913– 9925, doi:10.1002/2016JA022813.
- 408 Chen, L., Zhu, H., & Zhang, X. (2019). Wavenumber analysis of EMIC waves. *Geophysical*
409 *Research Letters*, 46, 5689– 5697. <https://doi.org/10.1029/2019GL082686>
- 410 Darrouzet, F., De Keyser, J., Décréau, P. M. E., El Lemdani-Mazouz, F., and Vallières, X.:
411 Statistical analysis of plasmaspheric plumes with Cluster/WHISPER observations, *Ann. Geophys.*,
412 26, 2403–2417, <https://doi.org/10.5194/angeo-26-2403-2008>, 2008.
- 413 Engebretson, M. J., Posch, J. L., Capman, N. S. S., Campuzano, N. G., Bělik, P., Allen, R. C., et
414 al. (2018). MMS, Van Allen Probes, GOES 13, and ground-based magnetometer observations of
415 EMIC wave events before, during, and after a modest interplanetary shock. *Journal of Geophysical*
416 *Research: Space Physics*, 123, 8331–8357. doi:10.1029/2018JA025984
- 417 Fraser, B. J., R. S. Grew, S. K. Morley, J. C. Green, H. J. Singer, T. M. Loto'aniu, and M. F.
418 Thomsen (2010), Storm time observations of electromagnetic ion cyclotron waves at
419 geosynchronous orbit: GOES results, *J. Geophys. Res.*, 115, A05208, doi:10.1029/2009JA014516.
- 420 Grach, V. S., Artemyev, A. V., Demekhov, A. G., Zhang, X.-J., Bortnik, J., and Angelopoulos,
421 V. (2024). Electron precipitation driven by EMIC waves: Two types of energy
422 dispersion. *Geophysical Research Letters*, 51, e2023GL107604. doi:10.1029/2023GL107604
- 423 Grison, B., Santolík, O., Lukačević, J., & Usanova, M. E. (2021). Occurrence of EMIC waves in
424 the magnetosphere according to their distance to the magnetopause. *Geophysical Research*
425 *Letters*, 48, e2020GL090921. <https://doi.org/10.1029/2020GL090921>
- 426 Hendry, A. T., Rodger, C. J., and Clilverd, M. A. (2017), Evidence of sub-MeV EMIC-driven
427 electron precipitation, *Geophys. Res. Lett.*, 44, 1210– 1218, doi:10.1002/2016GL071807.
- 428 Hanzelka M, Li W and Ma Q (2023), Parametric analysis of pitch angle scattering and losses of
429 relativistic electrons by oblique EMIC waves. *Front. Astron. Space Sci.* 10:1163515. doi:
430 10.3389/fspas.2023.1163515
- 431 Hanzelka, M., Li, W., Qin, M., Capannolo, L., Shen, X., Ma, Q., et al. (2024). Sub-MeV electron
432 precipitation driven by EMIC waves through nonlinear fractional resonances. *Geophysical*
433 *Research Letters*, 51, e2023GL107355. <https://doi.org/10.1029/2023GL107355>

- 434 Hogan, B., Li, X., Zhao, H., Khoo, L., Jaynes, A., Kanekal, S., et al. (2021). Multi-MeV electron
435 dynamics near the inner edge of the outer radiation belt. *Geophysical Research Letters*, 48,
436 e2021GL095455. <https://doi.org/10.1029/2021GL095455>
- 437 Hogan, B., Li, X., Xiang, Z., Zhao, H., Mei, Y., O'Brien, D., et al. (2023). On the dynamics of
438 ultrarelativistic electrons (>2 MeV) near $L^* = 3.5$ during 8 June 2015. *Journal of Geophysical*
439 *Research: Space Physics*, 128, e2023JA031911. <https://doi.org/10.1029/2023JA031911>
- 440 Kennel, C. F., and H. Petschek (1966), Limit on stably trapped particle fluxes, *J. Geophys. Res.*,
441 71, 1–28.
- 442 Kim, G.-J., Kim, K.-H., Lee, D.-H., Kwon, H.-J., and Park, J.-S. (2016), Occurrence of EMIC
443 waves and plasmaspheric plasmas derived from THEMIS observations in the outer magnetosphere:
444 Revisit, *J. Geophys. Res. Space Physics*, 121, 9443– 9458, doi:10.1002/2016JA023108.
- 445 Kozyra, J. U., T. E. Cravens, A. F. Nagy, E. G. Fontheim, and R. S. B. Ong (1984), Effects of
446 energetic heavy ions on electromagnetic ion cyclotron wave generation in the plasmopause
447 region, *J. Geophys. Res.*, 89(A4), 2217–2233, doi:10.1029/JA089iA04p02217.
- 448 Lee, J. H., Turner, D. L., Toledo-Redondo, S., Vines, S. K., Allen, R. C., Fuselier, S. A., et al.
449 (2019). MMS measurements and modeling of peculiar electromagnetic ion cyclotron
450 waves. *Geophysical Research Letters*, 46, 11622–11631. doi:10.1029/2019GL085182
- 451 Li, W., Y. Y. Shprits, and R. M. Thorne (2007), Dynamic evolution of energetic outer zone
452 electrons due to wave-particle interactions during storms, *J. Geophys. Res.*, 112,
453 doi:10.1029/2007JA012368.
- 454 Liu, S., Xia, Z., Chen, L., Liu, Y., Liao, Z., & Zhu, H. (2019). Magnetospheric Multiscale
455 Observation of quasiperiodic EMIC waves associated with enhanced solar wind pressure.
456 *Geophysical Research Letters*, 46, 7096–7104. <https://doi.org/10.1029/2019GL083421>
- 457 Lyu, X., Ma, Q., Tu, W., Li, W., & Capannolo, L. (2022). Modeling the simultaneous dropout of
458 energetic electrons and protons by EMIC wave scattering. *Geophysical Research Letters*, 49,
459 e2022GL101041. <https://doi.org/10.1029/2022GL101041>
- 460 Meredith, N. P., R. M. Thorne, R. B. Horne, D. Summers, B. J. Fraser, and R. R. Anderson(2003),
461 Statistical analysis of relativistic electron energies for cyclotron resonance with EMIC waves
462 observed on CRRES, *J. Geophys. Res.*, 108(A6), 1250, doi:10.1029/2002JA009700.
- 463 Ma, Q., Li, W., Yue, C., Thorne, R. M., Bortnik, J., Kletzing, C. A., et al. (2019). Ion heating by
464 electromagnetic ion cyclotron waves and magnetosonic waves in the Earth's inner magnetosphere.
465 *Geophysical Research Letters*, 46, 6258– 6267. <https://doi.org/10.1029/2019GL083513>
- 466 Ma, Q., Connor, H. K., Zhang, X.-J., Li, W., Shen, X.-C., Gillespie, D., et al. (2020). Global survey
467 of plasma sheet electron precipitation due to whistler mode chorus waves in Earth's magnetosphere.
468 *Geophysical Research Letters*, 47, e2020GL088798. <https://doi.org/10.1029/2020GL088798>
- 469 Ma, Q., Li, W., Zhang, X.-J., Bortnik, J., Shen, X.-C., Connor, H. K., Boyd, A. J., Kurth, W. S.,
470 Hospodarsky, G. B., Claudepierre, S. G., Reeves, G. D., & Spence, H. E. (2021). Global Survey
471 of Electron Precipitation due to Hiss Waves in the Earth's Plasmasphere and Plumes. *Journal of*
472 *Geophysical Research: Space Physics*, 126(8), e2021JA029644.
473 <https://doi.org/10.1029/2021JA029644>

- 474 McFadden, J.P. et al. (2009). The THEMIS ESA Plasma Instrument and In-flight Calibration. In:
475 Burch, J.L., Angelopoulos, V. (eds) The THEMIS Mission. Springer, New York, NY.
476 https://doi.org/10.1007/978-0-387-89820-9_13
- 477 Mourenas, D., A. V. Artemyev, Q. Ma, O. V. Agapitov, and W. Li (2016), Fast dropouts of
478 multi-MeV electrons due to combined effects of EMIC and whistler mode waves, *Geophys. Res.*
479 *Letts.*, 43, doi:10.1002/2016GL068921.
- 480 Ni, B., R. M. Thorne, Y. Y. Shprits, and J. Bortnik (2008), Resonant scattering of plasma sheet
481 electrons by whistler-mode chorus: Contribution to diffuse auroral precipitation, *Geophys. Res.*
482 *Letts.*, 35, L11106, doi:10.1029/2008GL034032.
- 483 Ni, B., J. Bortnik, R. M. Thorne, Q. Ma, and L. Chen (2013), Resonant scattering and resultant
484 pitch angle evolution of relativistic electrons by plasmaspheric hiss, *J. Geophys. Res. Space*
485 *Physics*, 118, 7740–7751, doi:10.1002/2013JA019260.
- 486 Ni, B., Bortnik, J., Nishimura, Y., Thorne, R. M., Li, W., Angelopoulos, V., Ebihara, Y., &
487 Weatherwax, A. T. (2014). Chorus wave scattering responsible for the Earth's dayside diffuse
488 auroral precipitation: A detailed case study. *Journal of Geophysical Research: Space Physics*, 119,
489 897–908. <https://doi.org/10.1002/2013JA019507>
- 490 Ni, B., et al. (2015), Resonant scattering of outer zone relativistic electrons by multiband EMIC
491 waves and resultant electron loss time scales, *J. Geophys. Res. Space Physics*, 120, 7357– 7373,
492 doi:10.1002/2015JA021466.
- 493 Pedersen, A., et al. (2008), Electron density estimations derived from spacecraft potential
494 measurements on Cluster in tenuous plasma regions, *J. Geophys. Res.*, 113, A07S33,
495 doi:10.1029/2007JA012636.
- 496 Qin, M., Hudson, M., Millan, R., Woodger, L., & Shekhar, S. (2018). Statistical Investigation of
497 the Efficiency of EMIC Waves in Precipitating Relativistic Electrons. *Journal of Geophysical*
498 *Research: Space Physics*, 123(8), 6223–6230. <https://doi.org/10.1029/2018JA025419>
- 499 Qin, M., Hudson, M. K., Li, Z., Millan, R. M., Shen, X.-C., Shprits, Y. Y., et al. (2019).
500 Investigating loss of relativistic electrons associated with EMIC waves at low L values on 22 June
501 2015. *Journal of Geophysical Research: Space Physics*, 124, 4022–4036.
502 <https://doi.org/10.1029/2018JA025726>
- 503 Qin, M., Hudson, M., Millan, R., Woodger, L., & Shen, X. (2020). Statistical dependence of
504 EMIC wave scattering on wave and plasma parameters. *Journal of Geophysical Research: Space*
505 *Physics*, 125, e2020JA027772. <https://doi.org/10.1029/2020JA027772>
- 506 Qin, M., Li, W., Ma, Q., Woodger, L., Millan, R., Shen, X.-C., & Capannolo, L. (2021). Multi-
507 Point Observations of Modulated Whistler-Mode Waves and Energetic Electron Precipitation.
508 *Journal of Geophysical Research: Space Physics*, 126(12), e2021JA029505.
509 <https://doi.org/10.1029/2021JA029505>
- 510 Qin M, Li W, Ma Q, Shen X-C, Woodger L, Millan R and Angelopoulos V (2024a) Large-scale
511 magnetic field oscillations and their effects on modulating energetic electron precipitation. *Front.*
512 *Astron. Space Sci.* 11:1253668. doi: 10.3389/fspas.2024.1253668.
- 513 Qin, M., Li, W., Shen, X.-C., Angelopoulos, V., Selesnick, R., Capannolo, L., et al.
514 (2024b). Global survey of energetic electron precipitation at low Earth orbit observed by

- 515 ELFIN. Geophysical Research Letters, 51,
516 e2023GL105134. <https://doi.org/10.1029/2023GL105134>
- 517 Qin, M., Li, W., et al. (2025), Dataset for Sub-MeV Electron Precipitation Driven by EMIC waves
518 in Plasmaspheric Plumes at High L shells, [Dataset] <https://figshare.com/s/3ba1a0c2420eb0faeedc>.
- 519 Ross, J. P. J., Glauert, S. A., Horne, R. B., & Meredith, N. P. (2022). The importance of ion
520 composition for radiation belt modeling. *Journal of Geophysical Research: Space Physics*, 127,
521 e2022JA030680. <https://doi.org/10.1029/2022JA030680>
- 522 Roux, A., Le Contel, O., Coillot, C. et al. The Search Coil Magnetometer for THEMIS. *Space*
523 *Sci Rev* 141, 265–275 (2008). <https://doi.org/10.1007/s11214-008-9455-8>
- 524 Shen, X.-C., Li, W., Capannolo, L., Ma, Q., Qin, M., Artemyev, A. V., et al. (2023). Modulation
525 of energetic electron precipitation driven by three types of whistler mode waves. *Geophysical*
526 *Research Letters*, 50, e2022GL101682. <http://doi.org/10.1029/2022GL101682>
- 527 Shumko, M., Gallardo-Lacourt, B., Halford, A. J., Blum, L. W., Liang, J., Miyoshi, Y., et al.
528 (2022). Proton aurora and relativistic electron microbursts scattered by electromagnetic ion
529 cyclotron waves. *Frontiers in Astronomy and Space*
530 *Sciences*, 9. <https://doi.org/10.3389/fspas.2022.975123>
- 531 Summers, D., Ni, B., & Meredith, N. P. (2007). Timescales for radiation belt electron acceleration
532 and loss due to resonant wave-particle interactions: 2. Evaluation for VLF chorus, ELF hiss, and
533 electromagnetic ion cyclotron waves: RADIATION BELT ELECTRON TIMESCALES. *Journal*
534 *of Geophysical Research: Space Physics*, 112(A4), <https://doi.org/10.1029/2006JA011993>.
- 535 THEMIS team. (2008), THEMIS, [Dataset] <http://themis.ssl.berkeley.edu/data/themis>.
- 536 Thorne, R.M., Horne, R.B., Jordanova, V.K., Bortnik, J. and Glauert, S. (2006). Interaction of
537 Emic Waves With Thermal Plasma and Radiation Belt Particles. In *Magnetospheric ULF Waves:*
538 *Synthesis and New Directions* (eds K. Takahashi, P.J. Chi, R.E. Denton and R.L.
539 Lysak). <https://doi.org/10.1029/169GM14>
- 540 Ukhorskiy, A. Y., Shprits, Y. Y., Anderson, B. J., Takahashi, K., and Thorne, R. M. (2010), Rapid
541 scattering of radiation belt electrons by storm-time EMIC waves, *Geophys. Res. Lett.*, 37, L09101,
542 <doi:10.1029/2010GL042906>.
- 543 Usanova, M. E., Mann, I. R., Bortnik, J., Shao, L., and Angelopoulos, V. (2012), THEMIS
544 observations of electromagnetic ion cyclotron wave occurrence: Dependence on AE, SYMH, and
545 solar wind dynamic pressure, *J. Geophys. Res.*, 117, A10218, <doi:10.1029/2012JA018049>.
- 546 Usanova, M. E., Darrouzet, F., Mann, I. R., and Bortnik, J. (2013), Statistical analysis of EMIC
547 waves in plasmaspheric plumes from Cluster observations, *J. Geophys. Res. Space Physics*, 118,
548 4946–4951, <doi:10.1002/jgra.50464>.
- 549 Usanova, M. E., Woodger, L. A., Blum, L. W., Ergun, R. E., Girard, C., Gallagher, D. L., et al.
550 (2024). H⁺, He⁺, He⁺⁺, O⁺⁺, N⁺ EMIC wave occurrence and its dependence on geomagnetic
551 conditions: Results from 7 years of Van Allen Probes observations. *Journal of Geophysical*
552 *Research: Space Physics*, 129, e2024JA032627. <https://doi.org/10.1029/2024JA032627>
- 553 Xiang, Z., Tu, W., Li, X., Ni, B., Morley, S. K., & Baker, D. N. (2017). Understanding the
554 mechanisms of radiation belt dropouts observed by Van Allen Probes. *Journal of Geophysical*
555 *Research: Space Physics*, 122, 9858–9879. <https://doi.org/10.1002/2017JA024487>

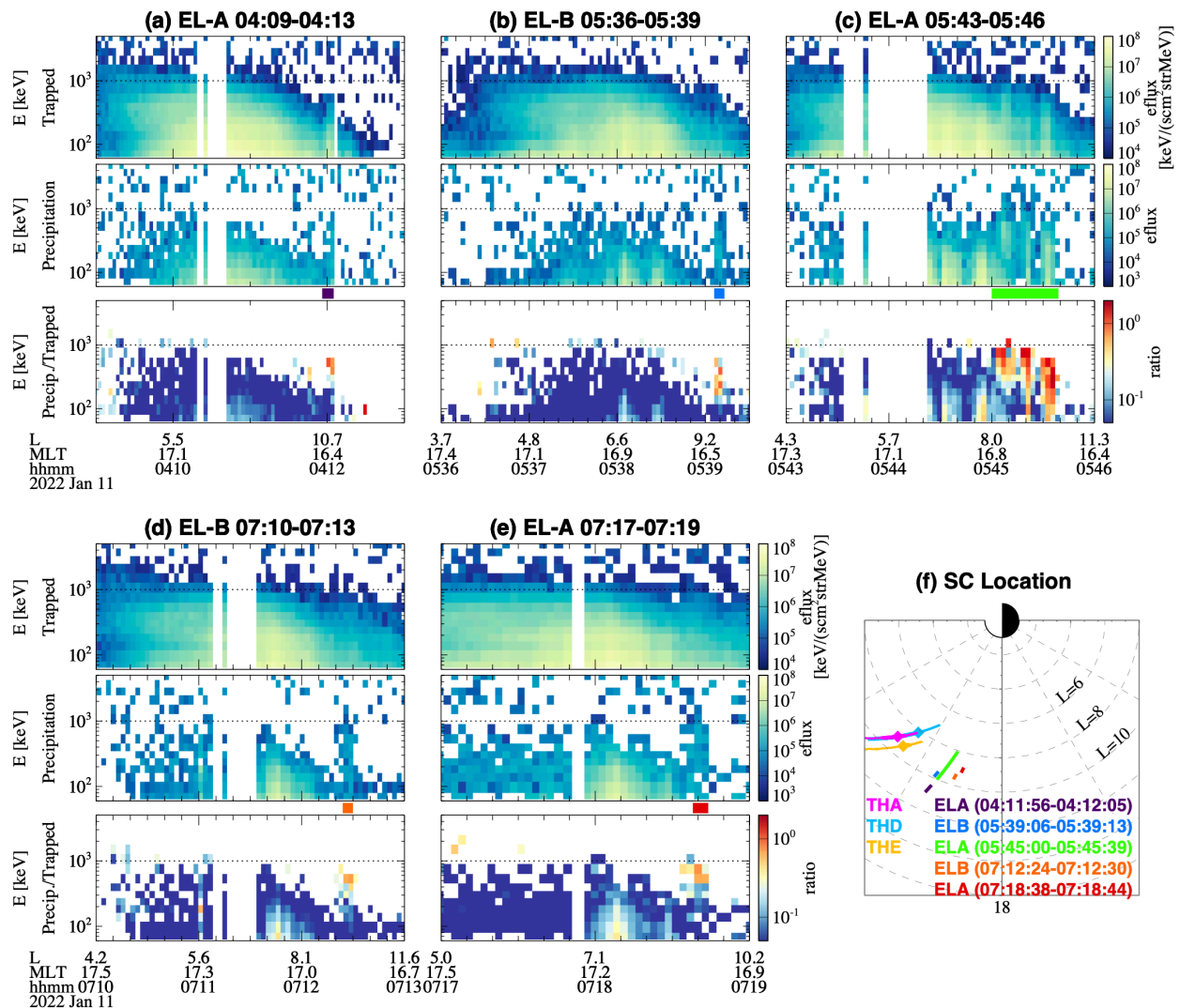
556 Yu, X., Yuan, Z., & Ouyang, Z. (2021). First observations of O2+ band EMIC waves in the
 557 terrestrial magnetosphere. *Geophysical Research Letters*, 48,
 558 e2021GL094681. doi:10.1029/2021GL094681

559 Zhang, X.-J., et al. (2016), Direct evidence for EMIC wave scattering of relativistic electrons in
 560 space, *J. Geophys. Res. Space Physics*, 121, 6620–6631, doi:10.1002/2016JA022521.

561 Zhang, X.-J., Mourenas, D., Shen, X.-C., Qin, M., Artemyev, A. V., Ma, Q., Li, W., Hudson, M.
 562 K., & Angelopoulos, V. (2021). Dependence of Relativistic Electron Precipitation in the
 563 Ionosphere on EMIC Wave Minimum Resonant Energy at the Conjugate Equator. *Journal of*
 564 *Geophysical Research: Space Physics*, 126(5), e2021JA029193.
 565 <https://doi.org/10.1029/2021JA029193>

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567 **Figures and Captions**

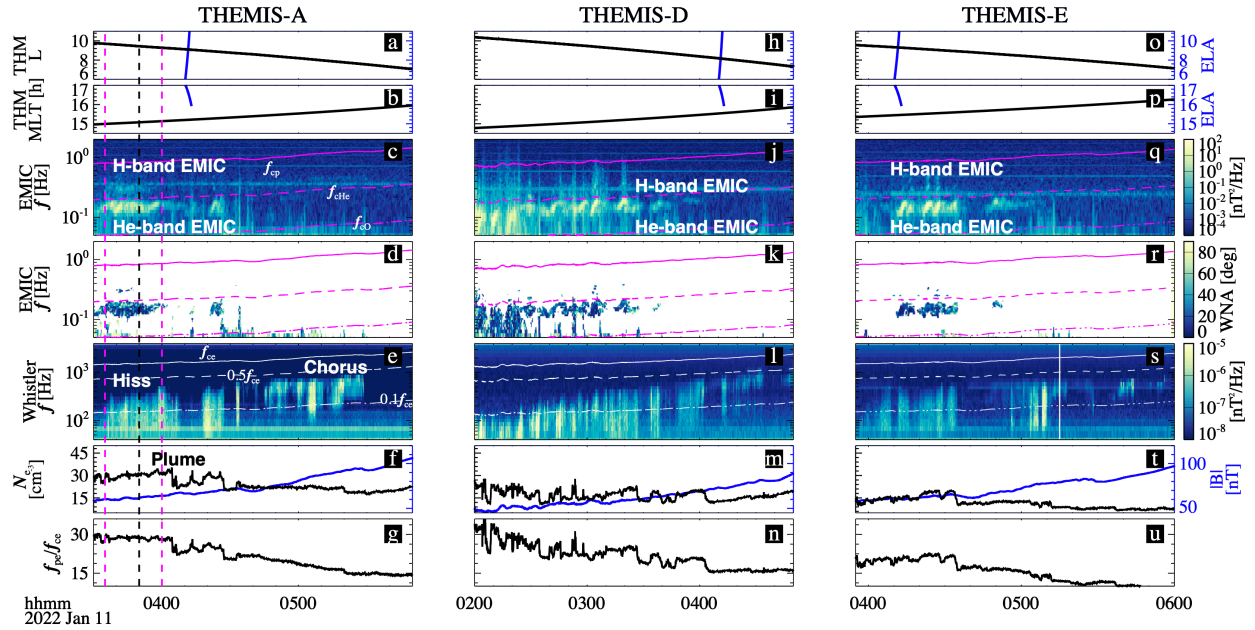


568

569 **Figure 1.** Overview of ELFIN-A and B observations during five consecutive orbits on 11 January
 570 2022. The top, middle, bottom panels in panels (a-e) show trapped electron energy fluxes,

571 precipitating electron energy fluxes and the precipitating-to-trapped ratio, respectively. The dashed
572 horizontal black lines in panels (a-e) show the 1 MeV energy. The color bars above the
573 precipitation ratio panels show the intervals with EMIC-driven signatures. Panel (f) shows the *L*-
574 MLT locations of the ELFIN CubeSats during the observed precipitation intervals (color bars) and
575 the THEMIS satellites in the conjugate locations. Superimposed thicker lines on the trajectories of
576 THEMIS represent the intervals when EMIC waves were observed. Diamonds represent the
577 location of THEMIS when electron precipitation was observed.
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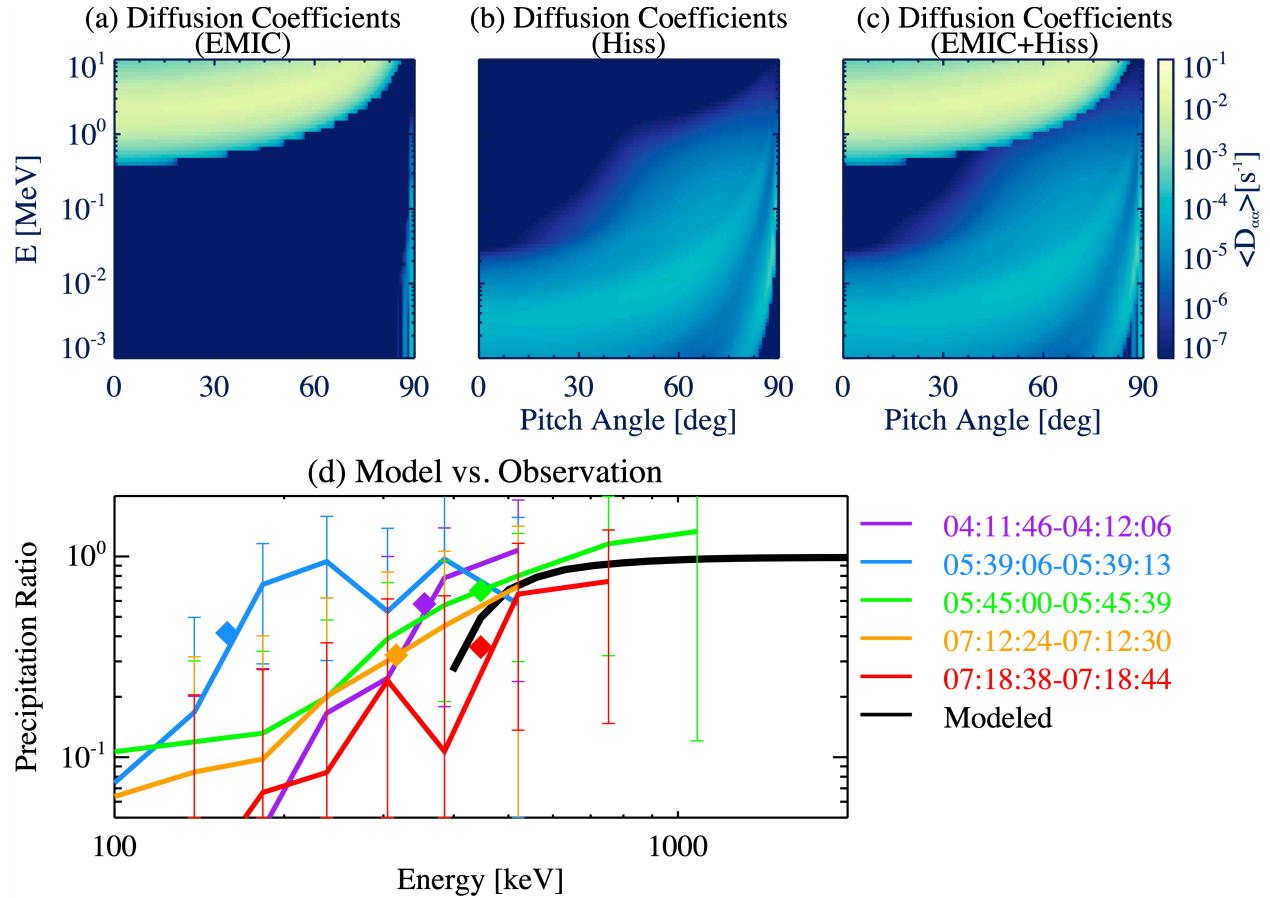
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581 **Figure 2.** Overview of the waves and background plasma conditions observed by THEMIS-A
 582 (left), D (middle) and E (right). (a) L-shell and (b) MLT of THEMIS (black lines) and ELFIN-A
 583 (blue lines) based on the TS05 magnetic field model; (c) magnetic spectral density over 0.02–2
 584 Hz, where the white lines represent proton, helium, and oxygen cyclotron frequencies; (d) EMIC
 585 wave normal angles; (e) magnetic spectral density over 40–4000 Hz, where the white lines
 586 represent the electron gyrofrequency (f_{ce} , solid), $0.5 f_{ce}$ (dashed) and $0.1 f_{ce}$ (dotted); (f) total
 587 electron density (black line) inferred from the spacecraft potential (Pedersen et al., 2008) and local
 588 magnetic field intensity (blue lines); (g) ratio of plasma frequency to electron gyrofrequency
 589 (f_{pe}/f_{ce}). The interval between the two dashed magenta lines is adopted to calculate the quasi-linear
 590 diffusion coefficients of He-band EMIC waves and hiss waves. The interval between the first
 591 magenta line and the dashed black line is adopted to calculate the quasi-linear diffusion coefficients
 592 of H-band EMIC waves. Panels (h)–(n) and (o)–(u) have the same format as panels (a)–(g), but
 593 observed by THEMIS-D and THEMIS-E, respectively.

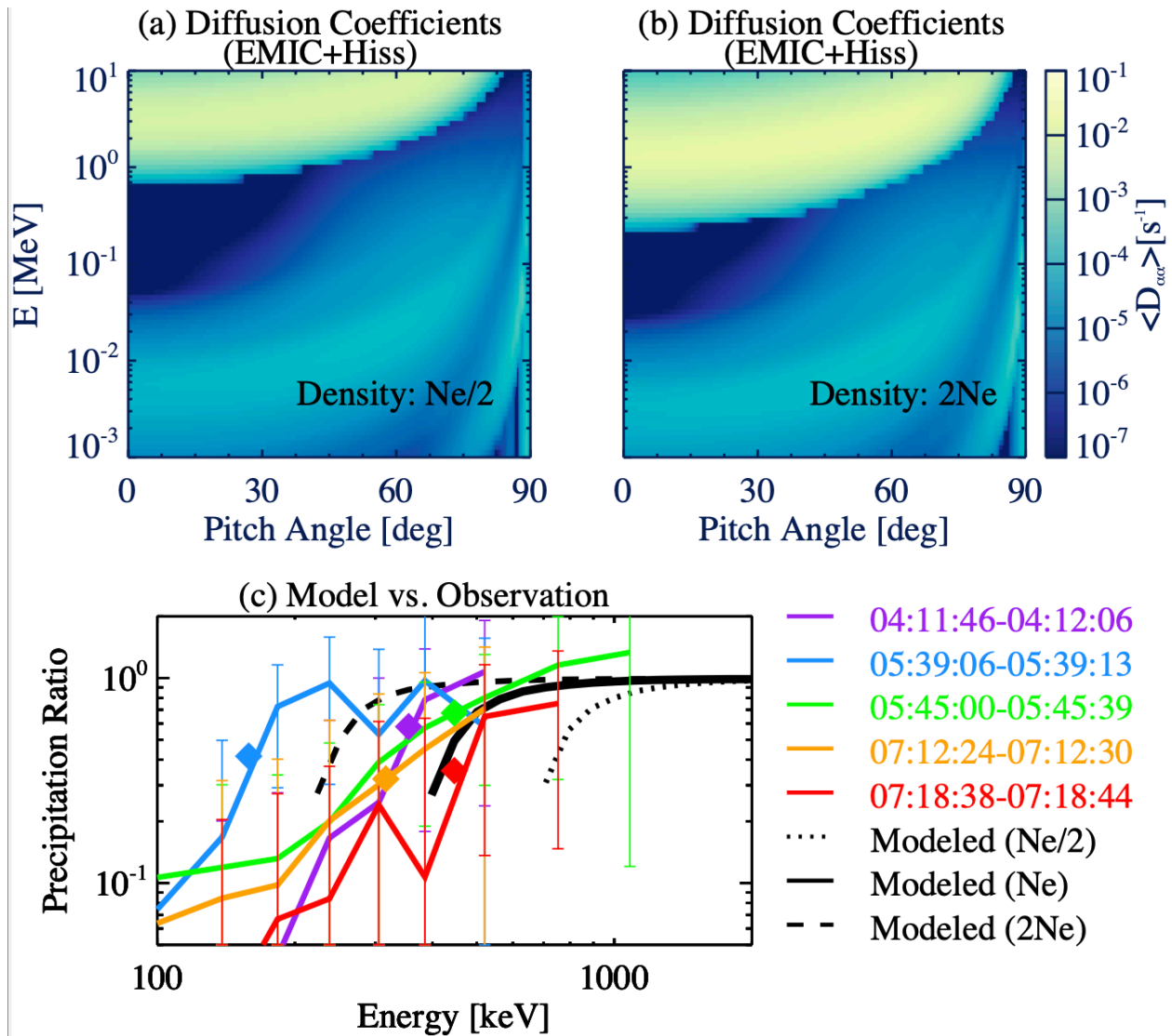
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596 **Figure 3.** Quasi-linear modeling of electron precipitation driven by EMIC waves and hiss waves
 597 observed by THEMIS-A. (a-c) Drift- and bounce-averaged pitch angle diffusion coefficients as a
 598 function of pitch angle and energy for (a) He-band EMIC waves (03:35-04:00 UT), (b) plume hiss
 599 waves (03:35-04:00 UT); (c) combined diffusion coefficients for He-band EMIC waves and hiss
 600 waves; (d) Comparison of the modeled precipitation ratio (loss cone filling index marked by the
 601 black lines) and the ELFIN observed electron precipitation ratio (purple, blue, green, orange and
 602 red lines) corresponding to the intervals with the labeled color bars shown in Figure 1. The black
 603 lines represent the modeled result with 1 (solid), 2 (dashed) and 0.5 (dotted) times of the measured
 604 electron density from THEMIS-A. The colored diamonds represent E_{min}^* , at which the measured
 605 precipitation ratio reaches half its peak value below the maximum. The colored error bars
 606 represent the mean error in determining the precipitation ratio from trapped and precipitating
 607 electron counts within the given period.

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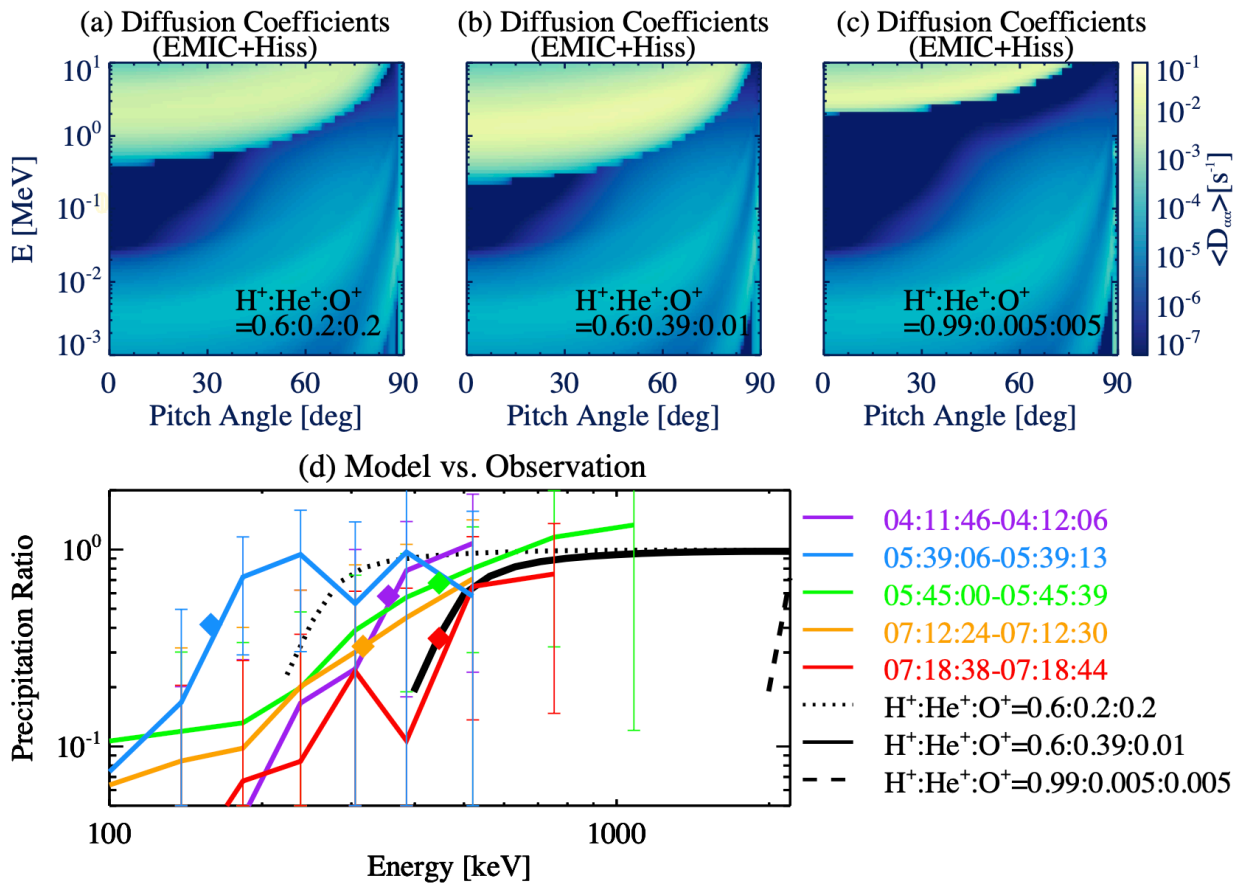


609

610 **Figure 4.** Quasi-linear modeling of electron precipitation driven by EMIC waves and hiss waves
 611 observed by THEMIS-A with various electron densities. The combined drift- and bounce-averaged
 612 pitch angle diffusion coefficients for He-band EMIC waves and hiss waves as a function of pitch
 613 angle and energy with the background electron density of (a) half and (b) double the measured
 614 density. (c) Similar to Figure 3d, except for the two additional black lines representing modeled
 615 precipitation ratio with 2 (dashed black line) and 0.5 (dotted black line) times the measured
 616 electron density from THEMIS-A.

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620 **Figure 5.** Quasi-linear modeling of electron precipitation driven by EMIC waves and hiss waves
 621 observed by THEMIS-A with various cold ion compositions. (a-c) Drift- and bounce-averaged
 622 pitch angle diffusion coefficients as a function of pitch angle and energy for cold ion composition
 623 H⁺: He⁺: O⁺ of (a) 0.6:0.2:0.2; (b) 0.8:0.1:0.1; (c) 0.99:0.005:0.005. (d) Similar to Figure 3d, except
 624 for the three black lines representing modeled precipitation ratios with cold ion compositions H⁺:
 625 He⁺: O⁺ of 0.6:0.2:0.2 (dotted), 0.6:0.39:0.01 (solid) and 0.99:0.005:0.005 (dashed), respectively.

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